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AXIAL COMPRESSION OF ALUMINUM CLOSED-CELL FOAM FILLED AND EMPTY ALUMINUM TUBES

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ABSTRACT:
Aluminum closed-cell foam filled aluminum tubes with a polyester bonding layer between foam core and tube wall have been compression tested in order to determine specific energy absorption for the crash box applications. Aluminum foam, empty and foam filled tubes without bonding layer were also tested for comparison purposes. Preliminary results have shown that interaction effect has been found in foam filled tubes with polyester layer. In order to identify deformation mechanisms involving with tube deformation, deformed empty and foam filled tubes cross-sections were microscopically analyzed and operative deformation mechanisms were determined.

Keywords: Aluminum foam, aluminum tube, energy absorption, crash box.

1. INTRODUCTION

Passenger safety and material damage are two important factors in designing of today's cars against accidents. Recent studies have shown that the crash boxes inserted between chassis and bumper are effective in reducing chassis damage until the speed of 15 km/h accidents [1]. Thin-walled tubes of aluminum have been widely investigated for the crash box applications because they are comparatively light and deform almost at a constant load under compressive loads, making their energy absorption efficiencies relatively high [2, 3]. Recent studies have also shown that when tubes filled with light weight aluminum foams, the specific energy increases over the energy absorption of foam alone plus empty tube (foam+tube), which is known as interaction effect [2, 4].

This study aims at determining the crushing behavior of Al closed-cell foam filled extruded aluminum tubes in the presence of a bonding material between foam core and tube wall. Foam, empty tube and filled tube without bonding layer were also tested for comparison purposes. The deformation cross-sections of the empty and foam filled tubes were microscopically analyzed in order to identify typical deformation mechanisms.

2. MATERIALS AND TESTING

The drawn aluminum tubes (3003-H14) were 15.88 mm in diameter with a wall thickness of 0.85 mm. Before foam filling, 20 mm long tube samples to be used in compression tests were cut using a diamond saw machine. Some of these samples were filled with foam plus a polyster layer between foam core and tube wall as shown in Figure 1. The weight and dimensions of the tubes and foams before and after filling were measured in order to calculate density of the foam and weight of the polyester layer. Two approaches were taken to fill the tubes with foam. In the first method, the empty tube was filled with polyester resin-curing agent mixture and then foam sample having outer diameter same as inner diameter of the tube was inserted inside the tube. Finally, the excessive bonding material was removed and tube, foam and bonding material were cured at room temperature. In the second method, foam was tightly inserted inside the tube without polyester layer. The thickness of the polyester layer was about 0.1 mm and its weight was therefore negligible compared to the foam and the tube weights.

Al closed-cell foams were prepared using a powder metallurgical technique patented by Fraunhofer Resource Center and detailed information on foam preparation is given elsewhere [5, 6]. Core-drilling was used to prepare foam samples with a diameter of 14 mm. The inner diameter of the tube and foam sample diameter were almost the same so that foam samples fitted tightly into the tube. The average density of the foam was 0.36 g/cm^{-3}.

Quasi-static compression tests were carried out on a Testometric Test Machine with a displacement rate of 0.01 mm s^{-1}. Tests were conducted axially (Figure 1) and the specific energy absorption was calculated from load-displacement curves. Interrupted tests were also used to make observations on the deformation cross-sections of the empty and foam filled tubes. These samples were cut axially and metallographically prepared for microscopic observations.

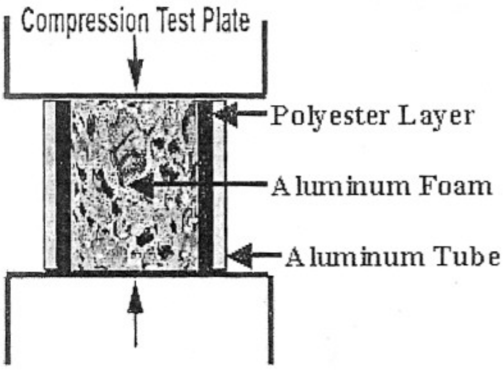

Figure 1 Schematic of foam filled Aluminum tube with a

polyester layer between foam and tube wall.

3. RESULTS AND DISCUSSION

Typical compression load-displacement curve of the empty Al tube is shown in Figure 2 together with micrographs of the deformed tube cross-sections corresponding various displacements on the curve. As shown in Figure 2, initially the tube deforms elastically (sample 1) until about peak load P_1 and thereafter localized deformation of concertina mode (axisymmetric folding) either at the bottom or top of the tube starts. Consequently, load decreases as the deformation proceeds in the fold region. In the region between P_1 and P_2, the length of the fold decreases progressively and simultaneously fold becomes wider (sample 2 and 3). When the lower edge of the fold is fully compressed to the compression test machine plate (Figure 1) the load starts to increase. At peak load P_3, the first fold is already fully compressed and the second fold emerges (sample 5). Following P_3, load decreases again as the second fold becomes wider (sample 6). At point P_4 the second fold lower edge is compressed completely over the first fold and therefore the load starts to increase again. This sequence of deformation, fold formation (drop of load) and fold densification (increase of load) continues until about all section of the tube is filled with the folds (sample 8).

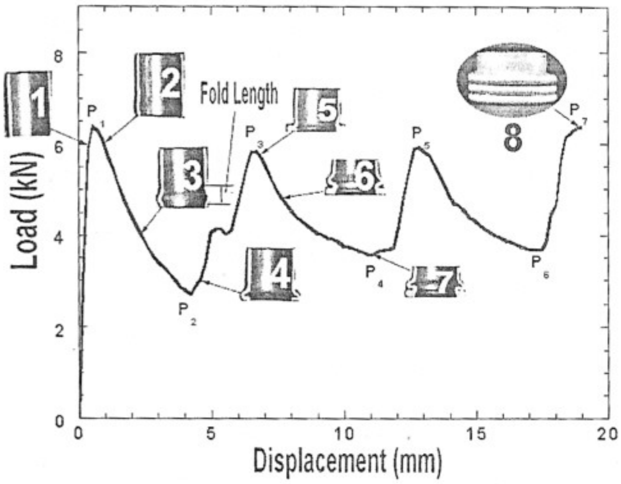

Figure 2 Load-displacement behavior of empty Al-tube with deformed cross-sections.

In Figure 2 two different fold formation modes are clearly seen; folds forming near to the compression test plate, either top or bottom of the tube and folds forming in the mid-sections of the tube following the first fold. The former induces a higher fold initiation peak load (P_1 and $P_7 > P_3$ and P_5) but a lower minimum load ($P_2 < P_4$ and P_6). Note that the deformation mode of the tested tube is concertina and the average crushing load (P_{avg}) for this mode is well approximated with the following equation [7];

$$P_{avr} = \sigma_y t \frac{6\sqrt{Dt}+3.44t}{0.86-0.57\sqrt{t/D}} \qquad (1)$$

where σ_y, t and D are the tube material yield stress (145 MPa), the tube thickness (0.85 mm) and mean tube diameter (15 mm). Using above equation, an average crushing load is calculated to be 4.5 kN for the tested Al tube. This is very similar to the average crushing load in Figure 2.

The load-displacement curves of the foam, empty tube and foam-filled tube with and without polyester layer are shown in Figure 3. In the same figure, the load sum of the foam alone and empty tube is also shown for comparison purposes. As seen in Figure 3, foam filled tube with a polyester bonding layer shows load values which are higher than those of foam filled tube without polyester and foam alone+empty tube. The load values of the foam filled tube without polyester and foam alone+empty tube are almost the same.

For the samples shown in Figure 3, the specific energy values were calculated using

$$S = \frac{\int P \, d\delta}{m} \qquad (2)$$

where S is the specific energy absorption, P is the load, δ is the displacement and m is the mass. The results of calculations are shown in Figure 4. The empty tube and the foam-filled tube have similar specific energy absorption values although the former is slightly more efficient.

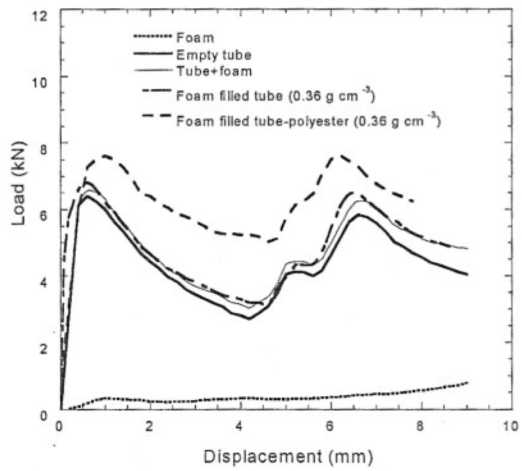

Figure 3 Load-displacement curves of foam, empty tube and foam-filled tubes.

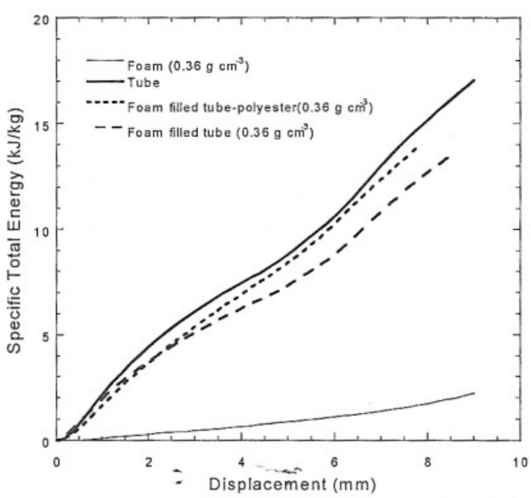

Figure 4 Specific energy versus displacement curves of foam, empty tube and foam filled tubes.

Microscopic analysis of the deformed foam-filled tubes with polyster has shown two different fold formations. In the first one, the first fold starts at the bottom or top of the tube (Figure 5(a)) and in the second it starts in mid-sections of the tube (Figure 5(b)). For both, the interaction effect is seen although the former initially shows a higher peak load. Note also that in the former, the folded region of the tube was separated from the foam core, but still the rest of tube stayed bonded to the foam core. In foam filled tubes without polyster layer, folding starts at the bottom or top of the tube and foam and tube deform independently.

Compression test load-displacement curves and calculated specific energy values of the foam filled tubes have shown that interaction effect is present if a bonding material used between foam and tube wall such as polyester used in this study. Results have also shown that both the fold initiation and fold deformation loads are higher in foam filled tubes. Although detailed mechanical tests and microscopic observations will be conducted, initial results have confirmed that foam core increases the resistance to fold formation. Similar observation have also made on similar foam filled tubes [2, 4].

Figure 5 Folds in foam filled Al tubes with polyester.

One of the advantages of foam filling is the tailoring of the specific energy absorption capacity using different foam densities and the interaction effect. The interaction effect might be due to filling of the fold with foam and/or the interfacial friction stress between foam and tube wall. In some of the tested samples, the folds were observed to be filled with foam. In these samples, load-displacement curve followed a more complex shape, which will be explored in the future.

The effect of foam material properties such as yield stress and the foam properties such as density on the energy absorption properties of the foam filled tubes will be investigated in more detail in the future. The reasons of interaction effect will be microscopically investigated also.

4. CONCLUSİONS

The crushing behavior of empty and aluminum closed-cell foam filled aluminum tubes was investigated under quasi-static compression loads. The empty tubes deformed in concertina mode and the mode of deformation was microscopically determined. In foam filled tubes with a polyester layer between foam core and tube wall an interaction effect has been found.

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